Somali Jet in the Arabian Sea, El Niño, and India Rainfall

DAVID HALPERN AND PETER M. WOICESHYN

Earth and Space Sciences Division, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

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ABSTRACT

Interannual variations of the Somali Jet in the Arabian Sea during 1988–99 were linked to El Niño and La Niña episodes and to India west coast rainfall. Onset dates and monthly mean strengths of the Somali Jet were described with Special Sensor Microwave Imager surface wind speeds. Each year the Somali Jet formed in a similar area in the western Arabian Sea, and always before the onset of monsoon rainfall in Goa. The average date of Somali Jet onset was two days later in El Niño events in comparison with La Niña conditions. Monthly mean strength of the Somali Jet was 0.4 m s^{-1} weaker during El Niño episodes than during La Niña intervals. When the monthly mean intensity of the Somali Jet was above (below) normal, there was an excess (deficit) of rainfall along the Indian west coast.

1. Introduction

The summer monsoon is inarguably an important facet of life in India, whether the aspect is economic (Webster et al. 1998) or cultural (Zimmermann 1987). Intense southwesterly surface winds in the Arabian Sea and heavy rainfall along the west coast of India are annual occurrences of the summer monsoon. For 2–3 months before monsoon onset, the wind is very weak (<4 m s^{-1}) and there is no rain from the cloudless sky. Monsoon onset has a duration of 6 days for wind in the Arabian Sea (Halpern and Woiceshyn 1999) and 3 days for rainfall in India (Das 1987).

Fieux and Stommel (1977) reported that 25 May, with a ±5-day uncertainty, is the average date of onset of monsoon winds in the Arabian Sea about 500 km northeast of Somalia. The location of the Fieux and Stommel (1977) site was predetermined by the intersection of two heavily traveled shipping lanes, which provided the unusual occurrence of daily wind observations. Monsoon wind onset time is not the same throughout the Arabian Sea (Halpern and Woiceshyn 1999). The Fieux and Stommel (1977) date of monsoon wind onset preceded the climatological-mean onset time of monsoon rainfall on the west coast of India. The average date of monsoon rainfall onset on the west coast of India, with a 7-day standard deviation, is 1 June at Trivandrum (8°N), 7 June at Goa (15°N), and 10 June at Bombay (19°N); (Das 1987).

A linkage between southwest monsoon wind in the Arabian Sea and India rainfall was indicated more than a quarter-century ago (Findlater 1969). As expected, large-scale monsoon rainfall accumulation over India and Southeast Asia and wind strength over the Arabian Sea and India are strongly correlated (Ju and Slingo 1995). In a diagnosis of surface wind vector patterns in the Arabian Sea to a degree of detail not possible in the past, Halpern and Woiceshyn (1999) showed that eastward expansion of the Somali Jet raised the intensity of surface wind convergence and, consequently, increased the amount of integrated cloud liquid water in the eastern Arabian Sea, which, presumably, influenced the rainfall of the west coast of India.

The Somali Jet is the narrow southwesterly surface wind with a 2-day average speed greater than 12 m s^{-1} (Halpern and Woiceshyn 1999); the cross-stream 1/*e* dimension of the Somali Jet is about 200 km. Halpern and Woiceshyn (1999) defined the onset of the Somali Jet to be the date when National Aeronautics and Space Administration (NASA) Scatterometer (NSCAT) surface wind speeds off Somalia reached 12 m s^{-1} over a 3° × 3° region in the western Arabian Sea for at least six days. The minimum duration was about three inertial periods, which is the approximate time for development of Ekman currents. The zonal component of wind direction must be eastward.

Only since 1988 have adequate surface wind data become available to describe the onset of the Somali Jet in the Arabian Sea and to investigate its interannual relationships with El Niño/La Niña and India rainfall.

Corresponding author address: Dr. David Halpern, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109-8099.
E-mail: david.halpern@jpl.nasa.gov

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However, studies with numerical weather prediction (NWP) wind data products have been made between the onset of southwest monsoon conditions and El Niño/La Niña (e.g., Joseph et al. 1994). The 1988–99 period includes episodes of El Niño and La Niña, but not a sufficient number of events occurred for results to have reliable statistics. Also, no dominant mode of interannual variability of southwest monsoon wind has been found (Annamalai et al. 1999), which illustrates the complexity of the monsoon and the difficulty to predict its interannual variability. The small record length and large intricacy of the Indian monsoon will preclude a definitive conclusion; our results may be considered a demonstration of concept.

An adaptation of the Arpe et al. (1998) conceptual model is explored for a teleconnection between the Somali Jet over the Arabian Sea and El Niño/La Niña. During El Niño, the convection area over the Indian subcontinent, which is the attractor for the Somali Jet, would move eastward and, consequently, subsiding air would replace rising air and the intensity of the rising air would be reduced. The minimum low atmospheric pressure would, as compared with La Niña, be greater in El Niño and would reach its minimum at a later date. For example, sea level atmospheric pressure at Bombay (Mumbai) was higher in the 1987 El Niño compared to the 1988 La Niña by about 2.7 hPa (Vernekar and Ji 1999); however, the occurrence of low (high) atmosphere pressure with La Niña (El Niño) conditions could have been coincidental because many factors influence the southwest monsoon. It is tempting to speculate that during El Niño the horizontal pressure gradient between the western Arabian Sea and India would be weaker to yield a Somali Jet of reduced strength. In addition, additional time would be required for the surface wind speed to reach 12 m s^{-1} and, consequently, Somali Jet onset would be delayed in El Niño as compared with La Niña.

2. Data and methods

a. Surface wind

1) SPECIAL SENSOR MICROWAVE IMAGER

We chose 1988 to be the beginning of the investigation because the first of a series of identical Special Sensor Microwave Imager (SSM/I) passive microwave instruments was launched in July 1987 on a U.S. Defense Meteorological Satellite Program (DMSP) spacecraft. The number of DMSP spacecraft providing SSM/I wind speed measurements was 1 in 1988–90, 2 in 1991–94, 3 in 1995–96, and then 4. In a 2-day interval, the number of 25 km $\times$ 25 km SSM/I wind speed measurements within 1° $\times$ 1° areas in the Arabian Sea varied from 20 to 80. The number of ship wind measurements and their areal coverage were inadequate to describe the onset of the Somali Jet over the Arabian Sea. We chose SSM/I data for analysis instead of an NWP surface wind data product because the NWP product fails to capture adequately wind variability having spatial scales smaller than 500 km (Halpern et al. 1999). Furthermore, the 2-day quantity of SSM/I data in a 1° $\times$ 1° area within a southwest monsoon season remained nearly uniform, in contrast to the wide range of numbers of in situ observations assimilated into the NWP forecast–analysis system. In addition, which NWP data product to use is debatable. In the Arabian Sea, two NWP 850-hPa June–September wind analyses differed from one another by more than 2 m s^{-1} (Annamalai et al. 1999) and two NWP monthly mean surface wind analyses differed from SSM/I wind speeds by 1–2 m s^{-1} (Ramesh Kumar et al. 1999). The level of physical oceanographic significance between monthly mean wind speeds is 1 m s^{-1} (Halpern et al. 1999). The European Remote-Sensing Satellite scatterometer, which began in July 1991, severely aliased the rapid onset of the Somali Jet because the single-sided scatterometer had a 3-day repeat cycle.

The SSM/I 10-m height wind speed data product is continuous, except for December 1987–January 1988, which has no influence on the analysis. SSM/I wind speeds produced by Wentz (1997), which had a 0.9 m s^{-1} root-mean-square (rms) difference relative to buoy data, were retrieved online at http://www.remss.com. For each day, the SSM/I data archive contains average wind speed recorded within ¼° $\times$ ¼° areas during descending orbit at about 0530–0830 local time, depending on spacecraft, and ascending orbit at about 1730–2030 local time, named ''SSMI/AM'' and ''SSMI/PM,'' respectively. Microwave electromagnetic radiation emitted by the sea surface is influenced by wind speed and, to a lesser extent, by wind direction (Wentz 1992). For the same surface wind speed and direction, the SSM/I on a descending orbit would retrieve a slightly different pattern of radiation than that recorded on an ascending orbit because the apparent surface wind directions associated with descending and ascending orbits differ by 180°.

2) SSMI/AM

For 15–16 June 1997, when the Somali Jet first appeared in 1997 (Halpern and Woiceshyn 1999), the correlation coefficient and rms difference between SSMI/AM and SSMI/PM wind speeds were 0.87 and 2.1 m s^{-1}, respectively. For a 2-day SSMI/AM wind speed of 12 m s^{-1}, the SSMI/PM speed predicted with a least square linear orthogonal regression analysis was 13.7 m s^{-1}. Therefore, conclusions based on appearance of a SSM/I specific isotach, for example, 12 m s^{-1}, are influenced by spacecraft direction. Also, caution is advised that results may have been slightly different had other SSM/I wind speed data products (e.g., Goodberlet et al. 1989; Bates 1991; Schluessel and Luthardt 1991) been used.

Subsequent analyses use SSMI/AM data which, when compared with SSMI/PM, had greater agreement with

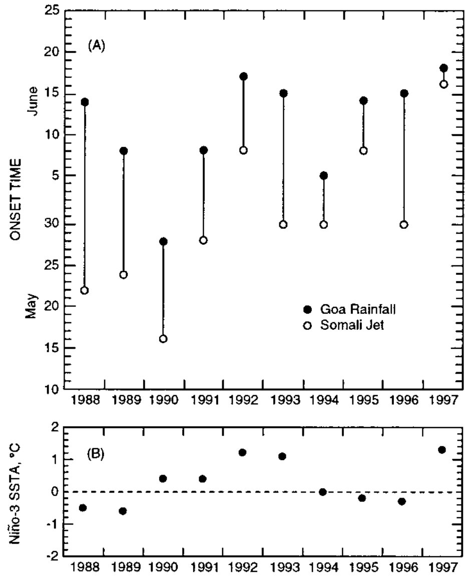

FIG. 1. (a) Onset time for Somali Jet in the western Arabian Sea and monsoon rainfall in Goa. (b) Niño-3 sea surface temperature anomaly in May or Jun in accordance with the month of the Somali Jet onset time.

2-day, 1° × 1° NSCAT data. For 15–16 June 1997, the correlation coefficient and bias between SSMI/AM and NSCAT speeds were 0.81 and 0.2 m s^{-1}, respectively. For an NSCAT wind speed of 12 m s^{-1}, the SSMI/AM wind speed computed from a least squares regression analysis was 12.5 m s^{-1}. We continued to use the NSCAT criterion of 12 m s^{-1} to define the Somali Jet because the 0.5 m s^{-1} difference between NSCAT and SSMI/AM speeds was much less than the 1.0 m s^{-1} threshold associated with significant differences between wind speeds. The SSM/I does not yield wind direction, notwithstanding the Atlas et al. (1996) SSM/I wind vector data product. During onset of the Somali Jet, the assumption that wind direction is toward India is very reasonable. No onset vortex (Krishnamurti et al. 1981) occurred during 1988–97 to disturb the steady westerly direction [see also, ''Weather, Monsoon Season (June–September)'' or ''Weather in India, Monsoon Season (June–September)'' in July editions of *Mausam*, 1989–98; July *Mausam* 1999 not available].

b. El Niño and La Niña

El Niño and La Niña have long been identified with interannual variations of India summer monsoon rainfall (e.g., Kane 1998). To investigate a correlative pattern between El Niño/La Niña and Arabian Sea monsoon winds, we develop a quantitative description of El Niño/La Niña because no universal definition exists.

El Niño and La Niña episodes correspond to 3-month average sea surface temperature anomalies above 0.2°C and below −0.2°C, respectively, in the Niño-3 (5°S–5°N, 150°–90°W) region. Monthly Niño-3 sea surface temperature anomalies were electronically retrieved from ftp://nic.fb4.noaa.gov/pub/cac/cddb/indices/sstoi.indices. El Niño or La Niña is not defined when the 3-month average Niño-3 sea surface temperature anomaly was less than |0.2|°C. This definition of El Niño and La Niña refers to the ''warming'' or ''cooling'' of surface waters in the equatorial eastern Pacific, and is less restrictive than other characterizations (Trenberth 1997).

Months used to determine El Niño or La Niña conditions associated with the onset of the Somali Jet were 2 months prior to the month in which onset occurred plus the onset month. For the El Niño/La Niña condition associated with the monthly mean strength of the Somali Jet, we use 2 months prior to the month under investigation plus the month being studied. For example, June 1988 was coincident with a La Niña episode because the average Niño-3 sea surface temperature anomaly during April, May, and June 1988 was −1.2°C.

c. Rainfall

1) GOA

Halpern and Woiceshyn (1999) defined the time of monsoon rainfall onset in Goa in 1997 to be the second day in a series of at least 3 consecutive days in which the daily average rainfall accumulation at four sites is greater than 5 cm. For 1988–97, we obtained India Meteorological Department (IMD) daily rainfall at Vengurla and Panjim, two coastal sites separated by 50 km near 15°N. Panjim is located in the state of Goa. Although Vengurla is situated several kilometers north of Goa, it is, for ease of discussion, considered to be in Goa. On many occasions rainfall amounts, even large amounts, at one station were not similar at the other station. Having data from two stations, the criterion for onset of monsoon rain was altered slightly from that described by Halpern and Woiceshyn (1999). The start of monsoon rains was the second of 3 days in which average rainfall in Goa in each of 2 consecutive days was above 5 cm and the 3-day accumulation was greater than 15 cm. After completing the analysis of onset times of Goa rainfall (Fig. 1), we found another source of onset times. Onset times of 1988–97 Goan monsoon rainfall were estimated from a diagram created at IMD and published in each July issue of *Mausam* during 1989–98 (July 1999 *Mausam* not available). IMD defined the onset of monsoon rainfall to be the middle day of a nonoverlapping pentad rainfall accumulation that had an abrupt increase in rainfall (Das 1987); also, the experience of the IMD forecaster plays a key role in declaring the date of monsoon onset (Joseph et al. 1994). IMD onset times of Goan rainfall were always earlier than values computed with daily rainfall data; average time difference was 5 days.

2) INDIA WEST COAST

Halpern and Woiceshyn (1999) suggested that the Somali Jet in the Arabian Sea and India west coast rainfall accumulation may have a causal relationship because of simultaneous increases in surface wind convergence and integrated cloud liquid water in the eastern Arabian Sea. SSM/I wind speed data cannot be used to calculate surface wind convergence. We allow the strength of the Somali Jet to be proportional to surface wind convergence in the eastern Arabian Sea because, presumably, the convergence was created, in part, by frictional retardation of the Somali Jet on encountering land. All-India rainfall is not believed to be responsive to the strength of the Somali Jet because India receives a large amount of monsoon rain from winds emanating from the Bay of Bengal.

We use monthly $2° \times 2°$ rainfall accumulations along India west coast from 8° to 22°N (Bell et al. 1999) for June, July, August, and September during 1988–98. The south-to-north longitudes of the center of each $2° \times 2°$ region were 77°, 75°, 75°, 73°, 73°, 73°, and 71°E. The mean 1988–97 India west coast rainfall accumulations in June (4297 mm), July (5476 mm), August (3165 mm), and September (1501 mm) were used to compute monthly mean rainfall accumulation anomalies.

3. Onset times of Somali Jet and rainfall in Goa

a. Somali Jet

The time of onset of the Somali Jet is the first 2-day interval of 3 consecutive 2-day intervals when the $1° \times 1°$ wind speed is above 12 m s^{-1} in a $3° \times 3°$ area in the western Arabian Sea. Times of onset of the Somali Jet (Fig. 1) were determined by visual inspection of maps of $1° \times 1°$ 2-day averaged SSMI/AM wind speeds in May and June of each year. The average date of onset during 1988–97 was 30 May. Average onset times for the Somali Jet during five El Niño and four La Niña episodes were 1 June and 29 May, respectively. The June 1994 Niño-3 sea surface temperature anomaly was too small for classification as El Niño or La Niña. The 2-day later arrival of the Somali Jet during El Niño compared to La Niña could be the result of sampling a time series of inadequate length or it could be evidence, albeit weak because of the small sample size and large dynamic range, for the Arpe et al. (1998) hypothesis.

The greatly delayed arrival of the Somali Jet in June 1997 further supports the Arpe et al. (1998) hypothesis because June 1997 was coincident with the most intense El Niño of the century. However, June 1997 was also coincident with an extensive warming of the Indian Ocean that Webster et al. (1999) and Saji et al. (1999) showed to be a phenomenon independent of the El Niño. The very late arrival of the Somali Jet in 1997 produced the two largest year-to-year fluctuations of onset time. Maximum year-to-year time difference was 1997–98 when the 1998 onset time (not shown) was 28 days earlier than in 1997 and the next largest variation of onset times was 17 days in 1996–97. The June 1997 anomalous onset time of the Somali Jet was one of many unusual ocean–atmosphere interactions in the north Indian Ocean (Annamalai and Slingo 1998; Lau and Wu 1999; Saji et al. 1999; Wang and Fan 1999; Webster et al. 1999; Yu and Rienecker 1999).

Annamalai and Slingo (1998) attributed the much delayed onset of the Somali Jet in 1997 to an easterly wind perturbation produced by the serendipitous passage of a Madden–Julian or intraseasonal oscillation. An intraseasonal oscillation propagates eastward along the equator, has a 10°–15° latitudinal extent, and is the dominant mode of atmospheric variability with timescales of about 1–10 weeks (Madden and Julian 1994). We described the intraseasonal oscillation occurrence as ‘‘serendipitous’’ because interannual variations of the strength and phase of intraseasonal oscillations are unpredictable (Slingo et al. 1999). At 60°–90°E, Slingo (1998), using an NWP data product, reported an intense westerly wind burst at 850 hPa during the first two weeks of May 1997 and easterly winds in early June 1997, which would reduce southwest monsoon wind speeds in the southern Arabian Sea to delay the onset of the 12 m s^{-1} isotach. In accord with the preceding speculation, the June 1997 mean $1° \times 1°$ surface wind speeds in the region where the Somali Jet formed were 0.5–1.5 m s^{-1} below the 1988–97 mean value (not shown). Also, Annamalai and Slingo (1998) reported the June–September 1997 Somali Jet at 850 hPa was weaker than normal.

The late onset of the Somali Jet in 1995 (Fig. 1) was caused by environmental conditions similar to those in May and June 1997 (Slingo 1998), which underscores the strong influence intraseasonal oscillations have on the onset of the Somali Jet. Anomalous wind conditions in June 1995, which are described in Section 4, were associated with the World Ocean Circulation Experiment (WOCE) Indian Ocean Expedition.

b. Monsoon rainfall in Goa

Times of onset of monsoon rainfall in Goa during 1988–97 are shown in Fig. 1. The average date of onset was 11 June.

c. Time interval between onsets of Somali Jet and Goan monsoon rainfall

Each year during 1988–97 the Somali Jet formed off Somalia before monsoon rains occurred in Goa (Fig. 1). The time interval between onsets of Goan rainfall and Somali Jet varied from 3 days in 1997 to 24 days in 1988; the average was 12 days.

4. Somali Jet strength

For June, July, August, and September, the 1988–97 monthly mean $1° \times 1°$ SSMI/AM wind speeds in the

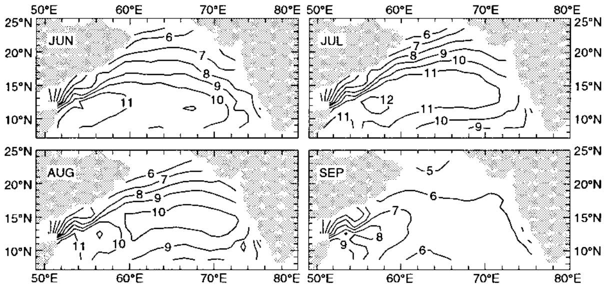

FIG. 2. Monthly mean 1° × 1° SSMI/AM wind speed averaged for 1988–97 for Jun, Jul, Aug, and Sep. The month is indicated in the upper-left corner of each panel.

Arabian Sea represented the climatological-mean monthly wind speed (Fig. 2). The 10-yr monthly mean June, July, and August wind speeds in the Somali Jet were about 2 m s^{-1} smaller than 60-yr climatological-mean monthly wind speeds computed by Hastenrath and Lamb (1979) from ship observations, which were collected at heights much higher than the 10-m height of SSM/I data. For 1-month timescale, the Somali Jet threshold wind speed was defined to be 10 m s^{-1}, which was lower than the threshold associated with 2-day 1° × 1° speeds because Halpern and Woiceshyn (1999) showed that the 2-day Somali Jet areal extent was not constant and the intensity expanded and contracted during a month.

The areal extent of the monthly mean Somali Jet varied considerably from month to month during the summer monsoon and from year to year. The average numbers of 1° × 1° areas occupied by the Somali Jet in June, July, August, and September were 111, 171, 78, and 5, respectively. In July the Somali Jet covered 55% of the Arabian Sea. Within the Somali Jet, the standard deviation of monthly mean wind speeds was less than 1 m s^{-1} (<10%), illustrating remarkable year-to-year steadiness.

Highest wind speed along a longitude defined the latitudinal position of the Somali Jet core speed which, in the western Arabian Sea, was ''anchored'' to a small area off Somalia during June–August (Figure 2). The path of the Somali Jet core speed in the Arabian Sea had least curvature in June, when it reached 12°N at 58°E. In July and August, the strongly curved trajectory of the Somali Jet core speed penetrated to 15°N at 63°–65°E. At the India west coast, wind speeds were below 10 m s^{-1}. Remnants of the Somali Jet entered India at 9°N in June and 13°–14°N in July and August.

The 1° × 1° monthly mean wind speed anomaly for a specific month (June, July, August, or September) was equal to the mean 1° × 1° wind speed for the specific

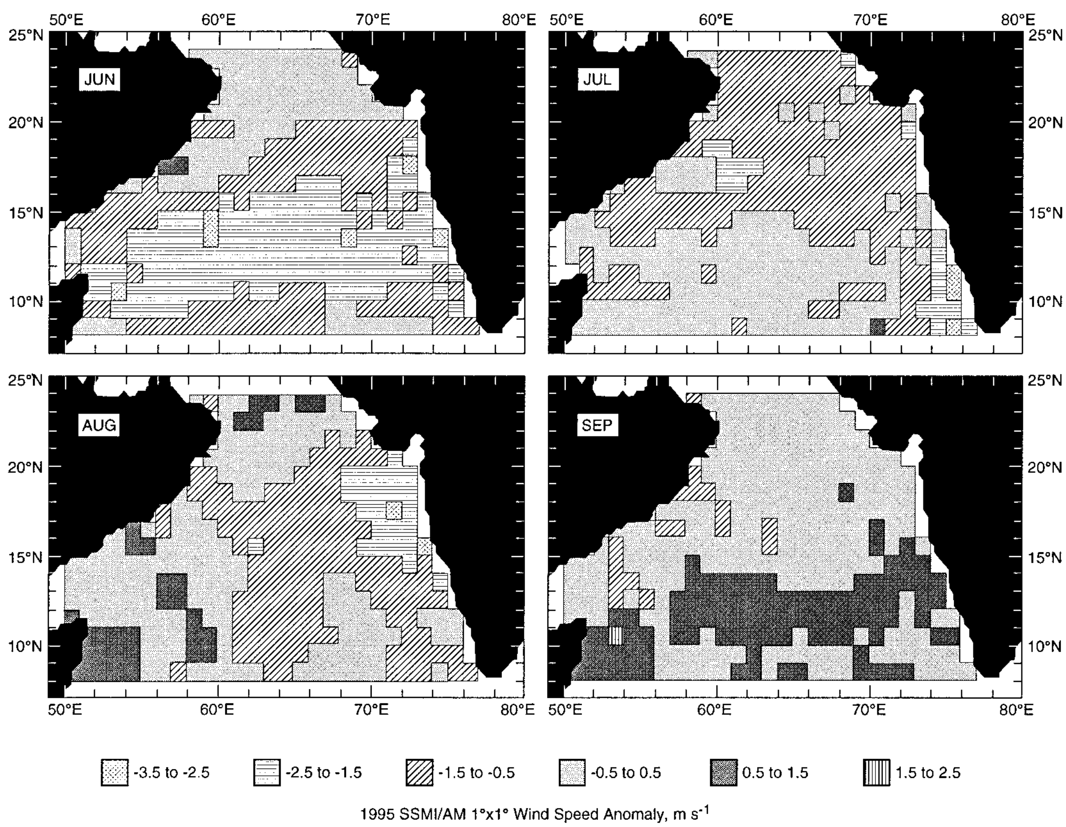

FIG. 3. Wind speed anomaly in m s^{-1} for (upper left) Jun, (upper right) Jul, (lower left) Aug, and (lower right) Sep 1995.

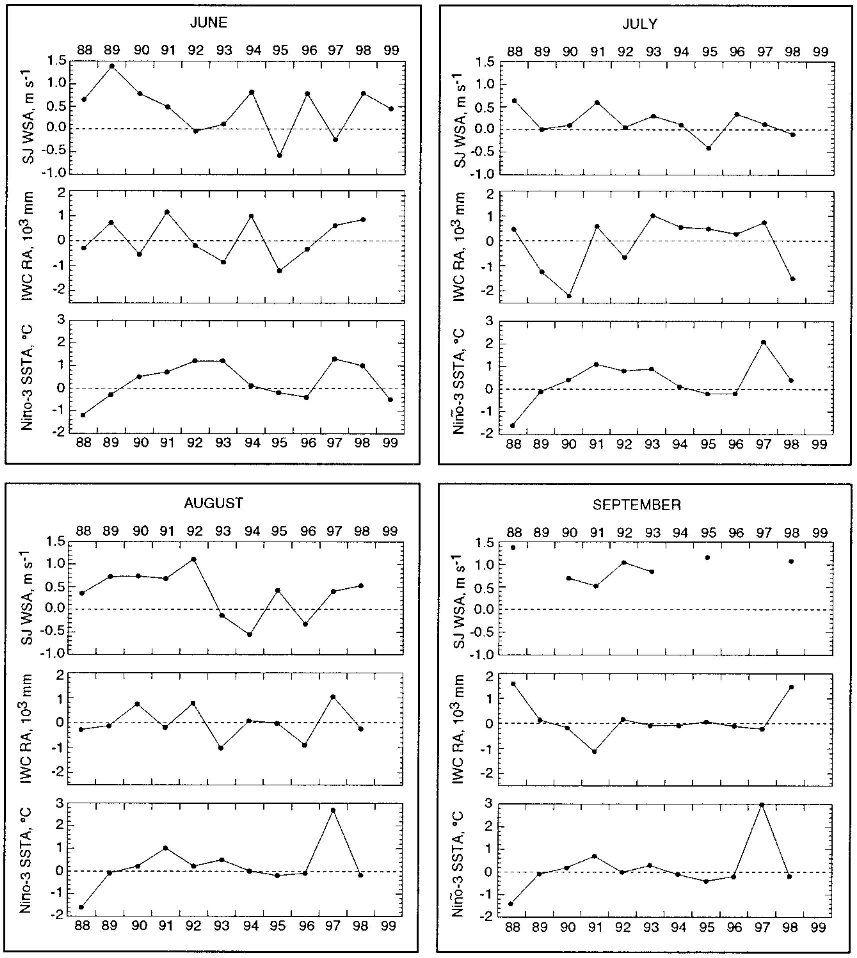

FIG. 4. Monthly mean Somali Jet wind speed anomaly named ''SJ WSA,'' India west coast rainfall anomaly named ''IWC RA,'' and Niño-3 sea surface temperature anomaly named ''Niño-3 SSTA,'' during 1988–99.

month minus the climatological-mean monthly $1° \times 1°$ wind speed. Wind speed anomaly differences between month-to-month distributions within a specific year (Fig. 3) had the same magnitude as interannual variations associated with a specific month (not shown). In 1995 during the WOCE Indian Ocean Expedition, wind speeds in the southern half of the Arabian Sea in June were about 2 m s^{-1} below normal and in September the southern one-third of the Arabian Sea was 1 m s^{-1} above normal (Fig. 3). A 2 m s^{-1} wind speed anomaly represented a difference from the 10-yr climatology of 2–2.5 standard deviations. Therefore, the June and September 1995 winds encountered by Chereskin et al. (1997), who measured upper-ocean currents along 8°30′N to estimate the wind-driven component of the circulation, were not normal.

The Somali Jet monthly mean wind speed anomaly is equal to the mean wind speed anomaly associated with the geographical region where monthly mean wind speeds were greater than 10 m s^{-1}. In Fig. 4, the 1988–97 average value of the Somali Jet wind speed anomalies for a specific month was not zero because the monthly mean areal extent and geographical domain of the Somali Jet were not constant. The Somali Jet was a permanent feature in June–August, occurring in each month in each of the 12 or 13 yr. In September, the Somali Jet was measured on 7 of 12 yr or slightly more than 50% of the time.

a. El Niño and La Niña

The June, July, August, and September Somali Jet monthly mean wind speed anomalies during El Niño were 0.2, 0.0, −0.2, and 0.5 m s^{-1} smaller than that during La Niña (Fig. 4). On 50% (25%) of occasions, the Somali Jet wind speed was lower (higher) during El Niño.

b. Rainfall

A pattern emerged in the 1988–98 anomalies of Somali Jet strength (Fig. 4) and India west coast rainfall

(Fig. 4), in accord with the suggestion by Halpern and Woiceshyn (1999). When the monthly mean intensity of the Somali Jet was above (below) normal, there was excess (deficit) rainfall along the India west coast. In June, the average rainfall accumulation associated with above-normal Somali Jet strength was 465 mm greater than the amount of rainfall coincident with a weaker-than-normal Somali Jet; the difference in Somali Jet strength was 1.0 m s^{-1}. In July and August, a stronger Somali Jet was accompanied with an excess of India west coast rainfall of 605 and 815 mm, respectively, in comparison with the rainfall when the Somali Jet intensity was below normal.

India west coast rainfall accumulation during 1988–98 was lower during El Niño in comparison with La Niña. In July and September, the India west coast received 745 and 1160 mm, respectively, more rain during La Niña as compared with El Niño. The 4-month India west coast rainfall anomaly (167 mm) associated with La Niña was 3 times greater than the rainfall anomaly deficit (84 mm) during El Niño. Apparently, the correlative pattern between June–September India west coast summer rainfall and El Niño/La Niña may have been stronger decades ago because the correlation coefficient between all-India summer monsoon rainfall and El Niño/La Niña was 95% significant during the past 150 yr except for the last 25 yr (Kumar et al. 1999).

5. Summary

Beginning in July 1987, the SSM/I yielded (and continues to yield) unprecedented spatial and temporal coverage of surface wind speed over the global ocean. Adequate SSMI/AM data existed to create 2-day $1° \times 1°$ wind speed distributions to determine the onset of the Somali Jet, which always preceded the onset of monsoon rainfall in Goa (Fig. 1). The onset time of the Somali Jet was 2 days later during El Niño as compared with La Niña (Fig. 1). The very late onset in 1997 accompanied the largest El Niño of the century. The strength of the Somali Jet was about 0.4 m s^{-1} lower during El Niño than in La Niña (Fig. 4). A stronger (weaker) than normal strength of the Somali Jet was associated with an excess (deficit) in India west coast rainfall. These features support the Arpe et al. (1998) hypothesis of a linkage between the Somali Jet in the Arabian Sea and El Niño/La Niña.

The very small sample size dictates that statistical confidence in the results is low and results may be considered to be a demonstration of concept.

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